United State Environmental Protection Agency

Office of Emergency Management
National Decontamination Team
Erlanger, Kentucky 41018

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Aerial and Ground Radiological Surveys Phosphate Mines in January 2011

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Executive Summary

In January 2011, EPA Region 4 initiated a joint ground-based radiological survey effort among the EPA Environmental Response Team (ERT), EPA Region 4, and the Department of Energy (DOE) Remote Sensing Laboratory (RSL) of a portion of the Coronet Superfund Site, near Plant City, Florida. During the ground-based survey effort, an aerial radiological survey was performed over the same area by the EPA Airborne Spectral Photometric Environmental Collection Technology (ASPECT) Program. Funding for the aerial survey was provided through an interagency agreement from the Federal Emergency Management Agency (FEMA), Nuclear Incident Response Team (NIRT) Program.

Operable Unit 2 (OU2) of the Coronet Superfund Site is a 1,500-acre parcel of land consisting of a series of water features resulting from former mine pits, mine spoil disposal areas, and areas disturbed by the former mining operations. This report presents the results from an aerial survey over OU2 conducted in January 2011. Some ground-based survey results are also included but a more comprehensive report on the ground-based results may be provided at a later date by EPA Region 4.

The objectives of the ground and aerial surveys were to:

1) Establish the range of radiation levels, in excess of background
2) Identify general categories of areas based on past use and radiation levels
3) Establish general boundaries of areas for further characterization assessment
4) Identify areas, as feasible, absent of radiation above background
5) Compare EPA and DOE ground-based data with ASPECT aerial survey data
6) Collect airborne data under a variety of flight parameters to help optimize future flight parameters (e.g., altitude vs line spacing)
7) Estimate surface uranium contamination levels using ASPECT data

The aerial survey was completed in a few hours and collected about 1,300 data points. The result showed:

1) Very good correlation and resolution with ground data
2) The site had several areas with distributed sources and exposure-rates ranging from background (about 5 to 10 μR/h) to about 50 μR/h
3) Airborne data identified areas of potential contamination that were not accessible by the ground teams
4) Environmental characterization flight parameters showed very little difference between 300 ft vs. 500 ft altitude and line spacing of no more than two times the survey altitude

The Discussion Section addresses the scientific validity and application of ground and airborne characterization data for environmental missions. Specific information about costs, products, and operational logistics are also provided.

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Acronyms and Abbreviations

AGL	above ground level
ASPECT	Airborne Spectral Photometric Environmental Collection Technology
Bi	bismuth
Ci	Curie
cps	counts per second
DOE	Department of Energy
EPA	Environmental Protection Agency
ERT	Environmental Response Team
eU	Equivalent Uranium based on ^{214}Bi region of interest
FEMA	Federal Emergency Management Administration
FOV	Field of view
ft	feet
FWHM	full width at half maximum
g	gram
GEM	Gamma Emergency Mapper
GPS	Global Positioning System
MeV	Mega electron volts
NaI(Tl)	sodium iodide thallium drifted detector
NIRT	Nuclear Incident Response Team
NORM	Naturally Occurring Radioactive Material
OU	Operable Unit
pCi	picocurie (10^{-12} Curies)
R	Roentgen
Ra	radium
Rn	radon
RSL	Remote Sensing Laboratory
TENORM	technologically enhanced naturally occurring radioactive material
U	uranium
µR hr	microRoentgen per hour (10^{-6} R hr)

1.0 Introduction

In January 2011, EPA Region 4 initiated a joint ground-based radiological survey effort among the EPA Environmental Response Team (ERT), EPA Region 4, and the Department of Energy (DOE) Remote Sensing Laboratory (RSL) of a portion of the Coronet Superfund Site, near Plant City, Florida. The EPA National Decontamination Team (NDT) assisted ERT with the ground-based survey by providing radiation detection equipment, vehicles, and personnel. During the ground-based survey effort, at the request of Region 4, an aerial radiological survey was performed over the same area of the ground-based efforts, by EPA Airborne Spectral Photometric Environmental Collection Technology (ASPECT) Program.

The objectives of the ground surveys were:

1) Establish the range of radiation levels, in excess of background, at Operable Unit 2 (OU2) of the Coronet Superfund Site
2) Identify general categories of areas based on past use and radiation levels
3) Establish general boundaries of areas for further characterization assessment
4) Identify areas, as feasible, absent of radiation above background

The objectives of the aerial survey were similar to the ground surveys that included:

1) A comparison between EPA and DOE ground-based data with ASPECT aerial survey data
2) Collect airborne data under a variety of flight parameters to help optimize future flight parameters (e.g., altitude vs. line spacing)
3) Estimate surface uranium contamination levels
4) Cross calibrate airborne with ground data

The ground survey was funded by EPA Region 4. The aerial survey was funded by an interagency agreement from the Federal Emergency Management Agency (FEMA), Nuclear Incident Response Team (NIRT) Program that provides funding to Federal partners to improve response and recovery activities following a radiological or nuclear incident.

2.0 Background and Survey Area Descriptions

The Coronet Phosphate Company began phosphate mining operations on a 2,500 acre site located in Plant City, Florida in 1906 and continued until about 1940. Early mining operations mainly involved the excavation of phosphate deposits and mechanical separation of pebble-size phosphate rock from the phosphate-sand-clay matrix. The spoils that contained smaller particles of phosphate rock, sand, and clay were deposited on various portions of the Site (such as land surface, pond bottoms, and construction sub-base).[1]

The 2,500 acre Coronet Superfund Site includes a former phosphate mining site and a closed chemical processing plant. It was divided by EPA into two Operable Units (OUs). OU1 is comprised of the 980-acre parcel located in the southeast portion of the Site consisting of a series of ponds and ditches associated with former mining operations, a water management system, the former main plant area, and a golf course. It was not the focus of this survey.

OU2 is a 1,500-acre parcel of land which was purchased for development and is referred to as Lakeside Station. Currently OU2 consists of a series of water features resulting from former mine pits, mine spoil disposal areas, and areas disturbed by the former mining operations. This report presents the results from an aerial survey over OU2 conducted in January, 2011. Some ground-based survey results are also included but a more comprehensive report on the ground-based results may be provided at a later date. The locations of the two OU's are shown in Figure 1, and are generally bound by US Highway 92 to the north; Park Road to the west; Coronet Road to the south and Lexie Lane to the east.

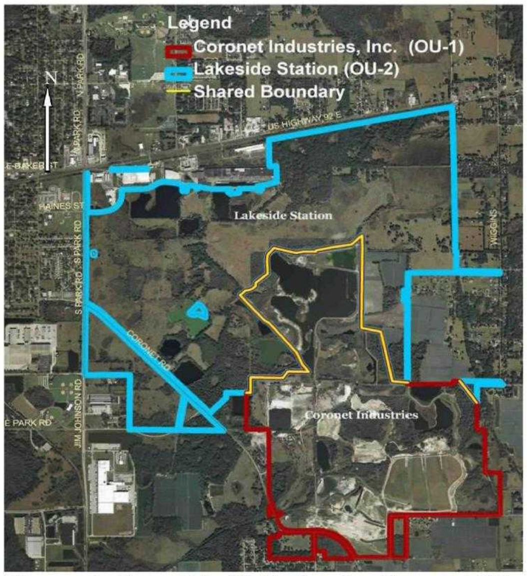


Figure 1: Operable Units for the Coronet Site

3.0 Flight Parameters

Figure 2: ASPECT Aircraft (Aero Commander 680 FL)

The ASPECT aircraft (Figure 2) used the following flight procedures for data collection on January 19, 2011:

Altitude above the ground level (AGL):
- 300 feet
- 500 feet

Target Speed: 100 knots (115 mph)

Line Spacing:
- 300 feet

One second data collection frequency

Figures 3 & 4 depict the aerial survey area containing 27 flight lines spaced 300 feet apart and 11 flight lines spaced 300 feet apart.

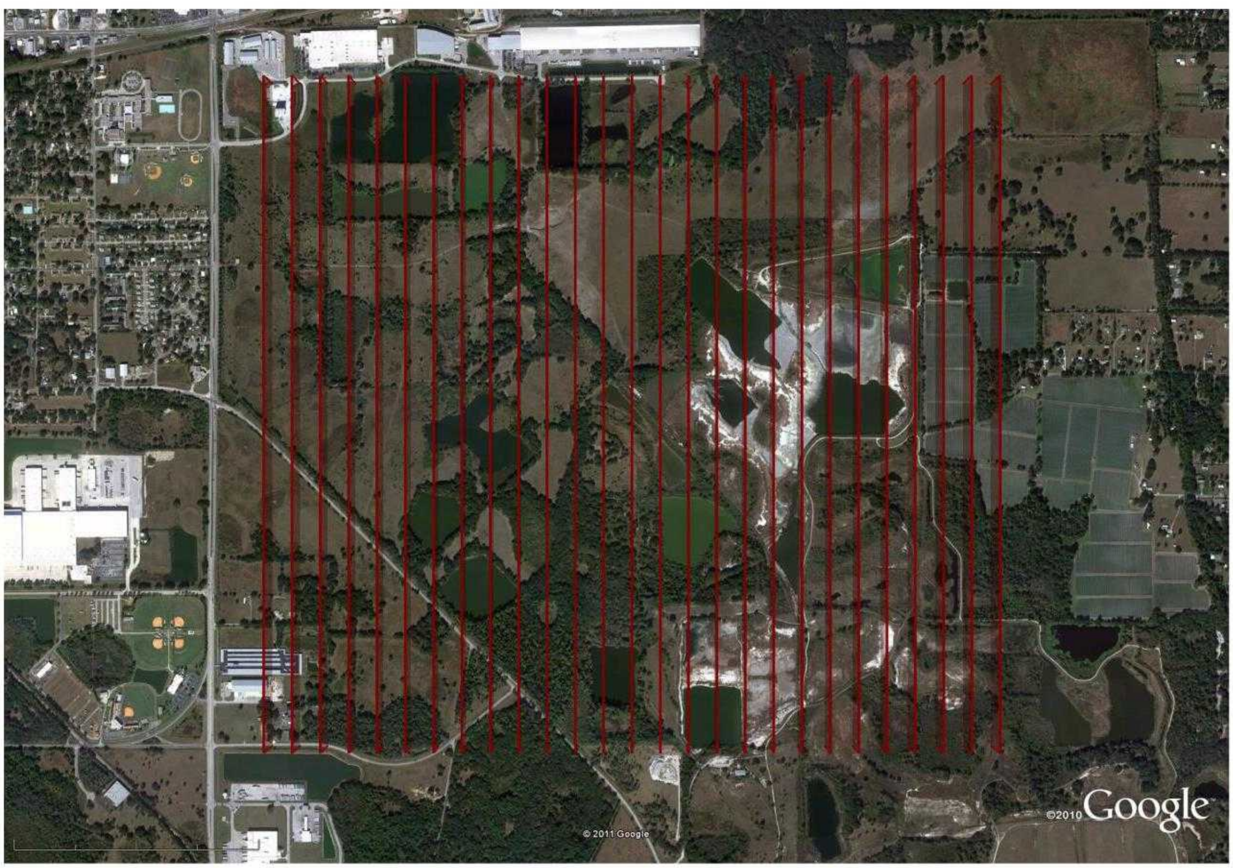


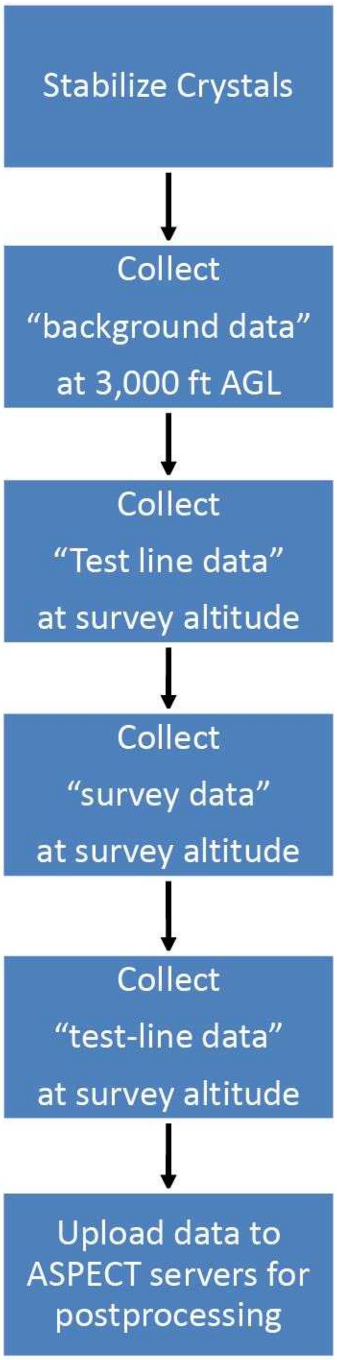
Figure 3: Operable Unit 2 flight lines for the aerial survey (300 ft aboveground level survey altitude with 300 ft line spacing)

Figure 4: Operable Unit 2 flight lines for the aerial survey (500 ft above ground level survey altitude with 300 ft line spacing)

4.0 Data Analysis

A unique feature of the ASPECT remote sensing technologies (see Appendix V) includes the ability to process spectral data automatically in the aircraft with a full reach back link to the program QA/QC program. As data is generated in the aircraft using the pattern recognition software, a support data package is extracted by the reach back team and independently reviewed as a confirmation to data generated on the aircraft.

Radiological spectral data are collected every second along with GPS coordinates and other data. These data are subject to quality checks within the Radiation Solutions internal processing algorithms (e.g. gain stabilization) to ensure a good signal. If no problems are detected, a green indicator light notifies the user that all systems are good. A yellow light indicates a gain stabilization issue with a particular crystal. This can be fixed by waiting for another automatic gain stabilization process to occur or the user can disable the particular crystal via the RadAssist Software application. A red light indicates another problem and would delay the survey until it can be resolved. If any errors are encountered with a specific crystal during the collection process, an error message is generated and the data associated with that crystal are removed from further analyses.



The data collection process used for this survey consisted of powering up the crystals and initiating the automated gain stabilization process. This process uses naturally occurring radioelements of potassium, uranium, and thorium to ensure proper spectral data collection.

The "background data" include radiation contributions from radon, cosmic, and aircraft sources. It does not include terrestrial radiation. Ideally, these data are collected over water at the survey altitude but when a large body of water does not exist, research has shown that an acceptable alternative is to collect data 3,000 ft above the ground (AGL).2 At this altitude atmospheric attenuation reduces the terrestrial radiation to a negligible level but is still low enough that cosmic radiation is not significant.

A "test line" is flown at survey altitude (300 feet AGL) near the survey area that is not expected to contain any elevated concentrations of NORM or manmade radionuclides. A second line is flown at the conclusion of the survey. If the difference between these lines exceeds 10 percent, then the survey data are corrected using a time-dependent linear interpolation correction factor.

Two software packages were used to generate products for this survey. The first was RadAssist Version 3.18.2.0 (Radiation Solutions, Inc., 386 Watline Avenue, Mississauga, Ontario, Canada) which produced contour plots of:

(1) **exposure rate** (microRoentgen per hour),
(2) **concentration contours for uranium** (pCi/g).

The second software package was ENVI® Version 4.7; ASPECT Version 8.5.12.7, Build 1102042120 (ITT Visual Information Solutions, Boulder, CO) which produced:

(3) **excess uranium** sigma point plots showing locations where ^{214}Bi was out of balance with the surrounding environment.

RAD Assist Method	**ENVI ASPECT Method**
↓	↓
Live time correction	Live time correction
↓	↓
Subtract cosmic and aircraft background contribution (coefficients)	Subtract cosmic and aircraft background contribution (3,000 ft AGL)
↓	↓
Radon contribution correction was not performed using RadAssist	"Test Line" (determines "normal") Height correction (μ=0.0017 m^{-1}) Calculate ^{214}Bi ROI K-value (median)
↓	↓
Perform stripping correction (ASPECT specific calibration coefficients were determined after these surveys)	Subtract radon contribution (Test Lines)
↓	↓
Perform height correction (μ=0.0050 m^{-1})	Determine net count rate for ^{214}Bi and standard deviation (sigma value; σ)
↓	↓
Perform exposure rate conversion (determined after these surveys)	Determine Sigma Values (<-6σ, -6 to -4; -4 to -2; -2 to 2; 2 to 4, 4 to 6, >6σ)
↓	↓
Create contour plots Exposure Rate (μR/h) Uranium Concentration (pCi/g)	Create excess Uranium point plots

Total count rate products illustrate gamma activity from all terrestrial sources after subtracting the "background data" contributions from radon, cosmic and aircraft sources. They can be used to assess the wide range of radioactivity present in the environment. The RadAssist calibration coefficients were determined based on methodology published by the International Atomic Energy Agency.[4] Radon was accounted for by using the ENVI code and DOE AMS algorithms by flying various test lines at the respective survey locations.

Excess uranium sigma points were determined using an algorithm published by the IAEA and incorporated into the ENVI software program. This algorithm is based on the assumption that natural background radioisotope contributions are stable over large geographical areas

(Appendix IV). This will result in a spectral shape that remains essentially constant over large count rate variations (Figure 5).

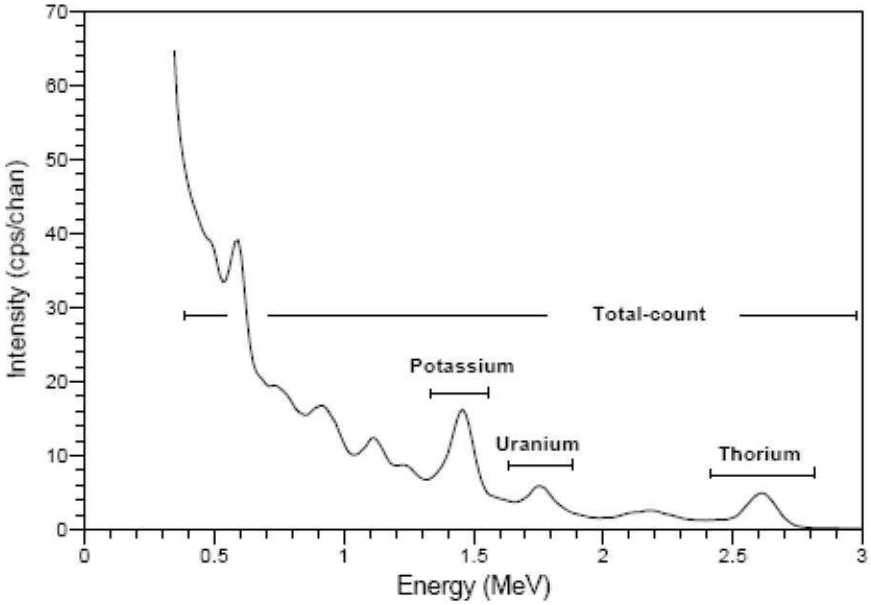


Figure 5: Typical airborne gamma ray spectrum showing positions of the conventional energy windows.
Adapted from IAEA-TECDOC-1363

To determine excess eU count rate, the region-of-interest around ^{214}Bi (labeled uranium above, 1659 keV to 1860 keV) is compared to the region-of-interest (ROI) represented by nearly the entire spectrum, called the Total Count ROI (36 keV to 3,027 keV).* The count rate ratio between these windows (e.g., Uranium ROI / Total Count Rate ROI) is relatively constant and is referred to as the "K" value. The actual windows (ROIs) used in this survey are shown in Appendix III. A K-value was determined from the "test line" data collected before and after each survey. The median K-value (e.g., most common K-value) was used in the algorithm to determine excess uranium.

K-value = $\dfrac{\text{Count rate in } \textbf{\textit{target}} \text{ region-of-interest}}{\text{Count rate in "Total Count" region-of-interest}}$

Excess activity can be estimated using the following formula:

Excess eU activity = **Measured** eU activity – **Estimated** eU activity

Where:

Measured eU activity = the measured count rate within the e**U** ROI during the survey

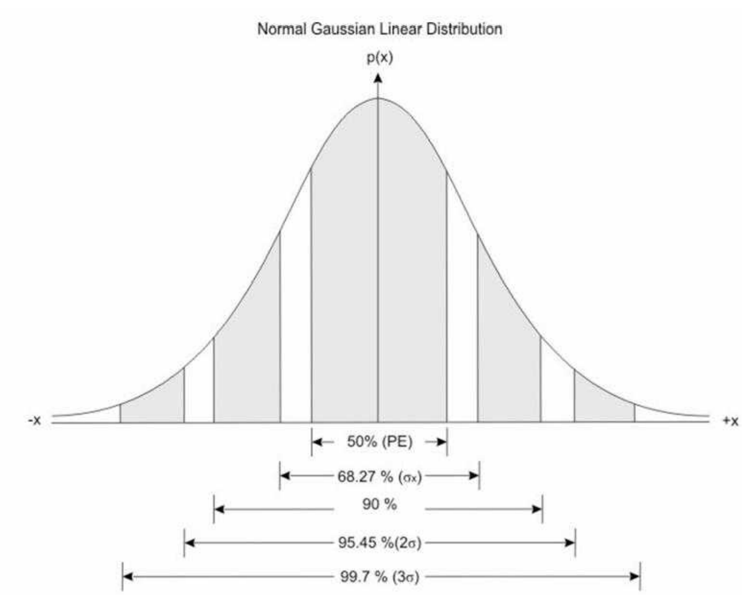
Estimated eU activity = **K-value** * measured count rate in Total Count ROI during the survey

* The Total Count ROI is an arbitrary selection. Recent discussions among Radiation Solutions, DOE AMS, and EPA ASPECT have resulted in a recommended Total Count ROI of channels 9 to 937 (30 keV to 2,814 keV).

The equation for excess activity becomes:

EXCESS U = Measured eU ROI – (K * Measured Total Counts ROI)

The most likely value of net "excess eU" should be zero, and since radiological disintegrations are randomly occurring events, the second-by-second "excess eU" results are statistically distributed about the mean in a normal Gaussian distribution (Figure 6).



Standard deviation (σ, sigma) represents the spread of the data about the mean. In this survey, the mean value (net "excess eU") was zero.

1 σ = 68.27% of the data
2 σ = 95.45% of the data
3 σ = 99.73% of the data
4 σ = 99.99366% of the data
5 σ = 99.99994% of the data
6 σ = 99.999999% of the data

Figure 6: Normal Gaussian Distribution and associated confidence intervals.

Every measurement was scored according to its "sigma" value and color coded according to the ranges in Figure 7. The color code and range were arbitrarily selected to limit the risk of false positives to 1 in about 15,800,000 samples (greater than or less than 6 sigma).

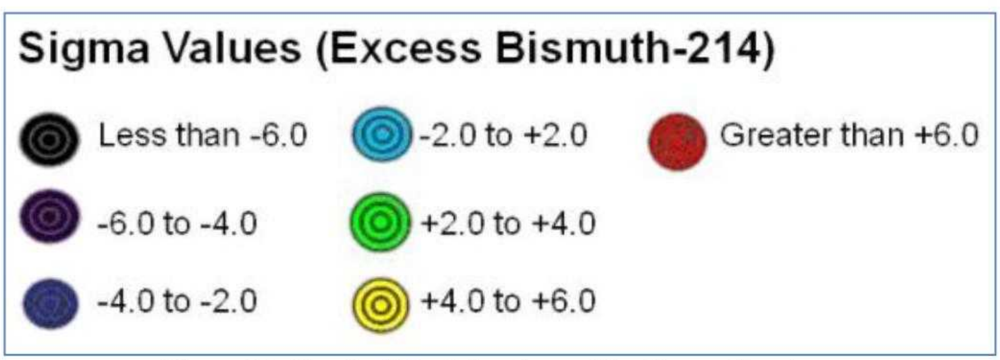


Figure 76: Standard Deviation Legend for Excess Uranium

5.0 Results

The aerial survey covered nearly 1,500 acres of land consisting of about 1,300 data points and the mission was completed within a few hours. During this survey, a joint ground-based survey was being conducted by EPA and DOE, providing a rare opportunity to validate airborne measurements with ground measurements. A sample of the ground-based survey results is used to illustrate correlation with airborne data (Figure 8). These results showed the following:

1) Very good correlation and resolution with ground data,
2) The site had several areas with distributed sources and exposure-rates* ranging from background (about 5 to 10 µR/h) to about 50 µR/h, and
3) Airborne data identified areas of potential contamination that were not accessible on the ground.

Radiological products included contour plots for exposure rate, uranium concentration (Figures 9 & 10) and an excess equivalent-uranium sigma plot, which represents the number of standard deviations from background (Figure 11).

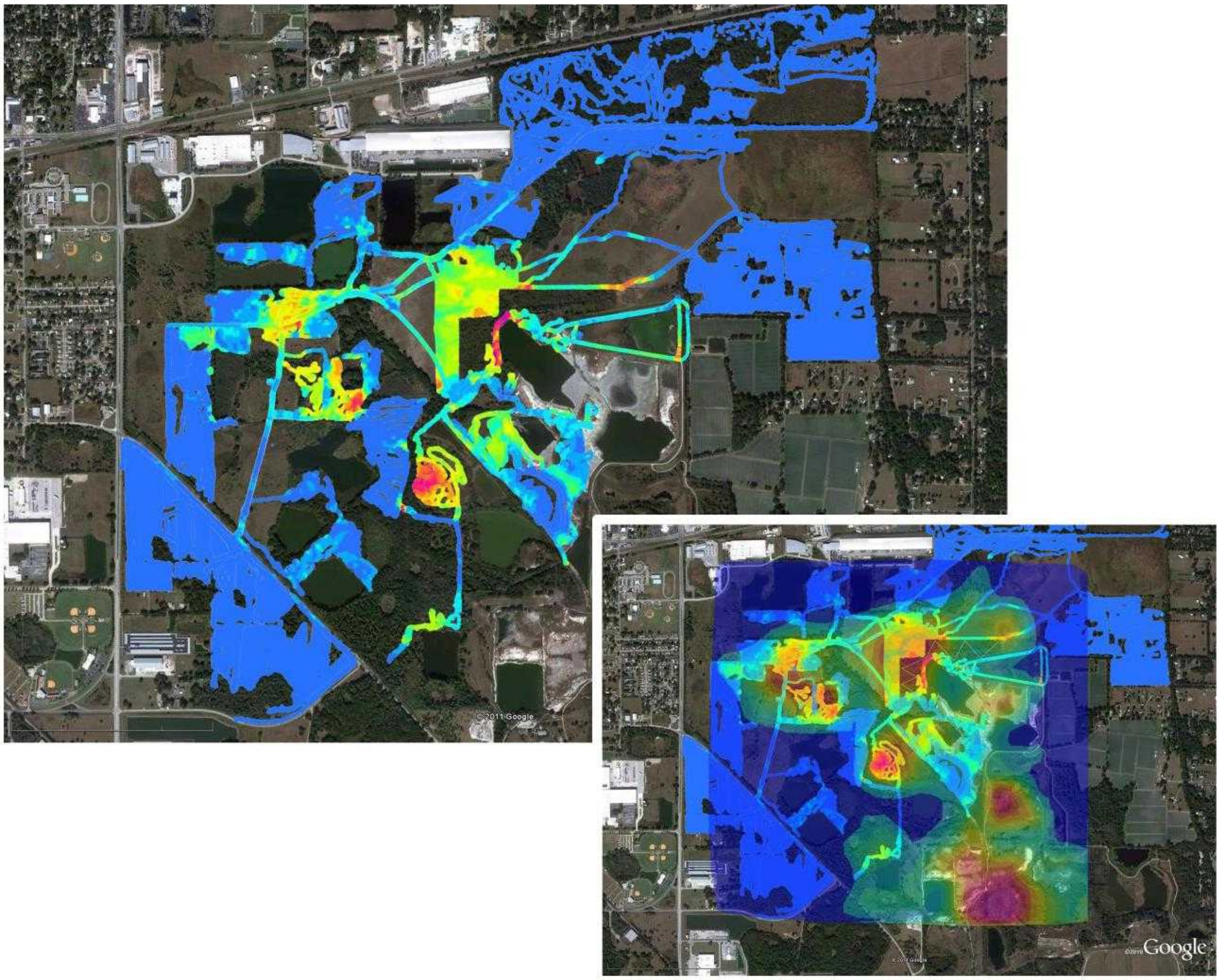
Pressurized ionization chamber (PIC) measurements on the ground were used to develop a site-specific calibration coefficient to convert airborne data to ground-based exposure rates. The associated exposure-rate contour map showed good correlation with the PIC measurements. Table 1 contains the estimated areas of the survey based on exposure rate.

Table 1. Approximate acreage exposure-rate contour range

Exposure Rate Range (µR/hr)	Percent of Total Area	Approximate Acreage
< 10	35.7%	522
10 to 15	15.0%	220
15 to 20	12.9%	189
20 to 25	12.8%	187
25 to 30	8.3%	121
35 to 35	6.0%	88
35 to 40	4.9%	72
40 to 45	3.3%	48
45 to 50	1.0%	15
> 50	0.1%	1
Totals	100.0%	1,463

* As measured 1 meter above the ground.

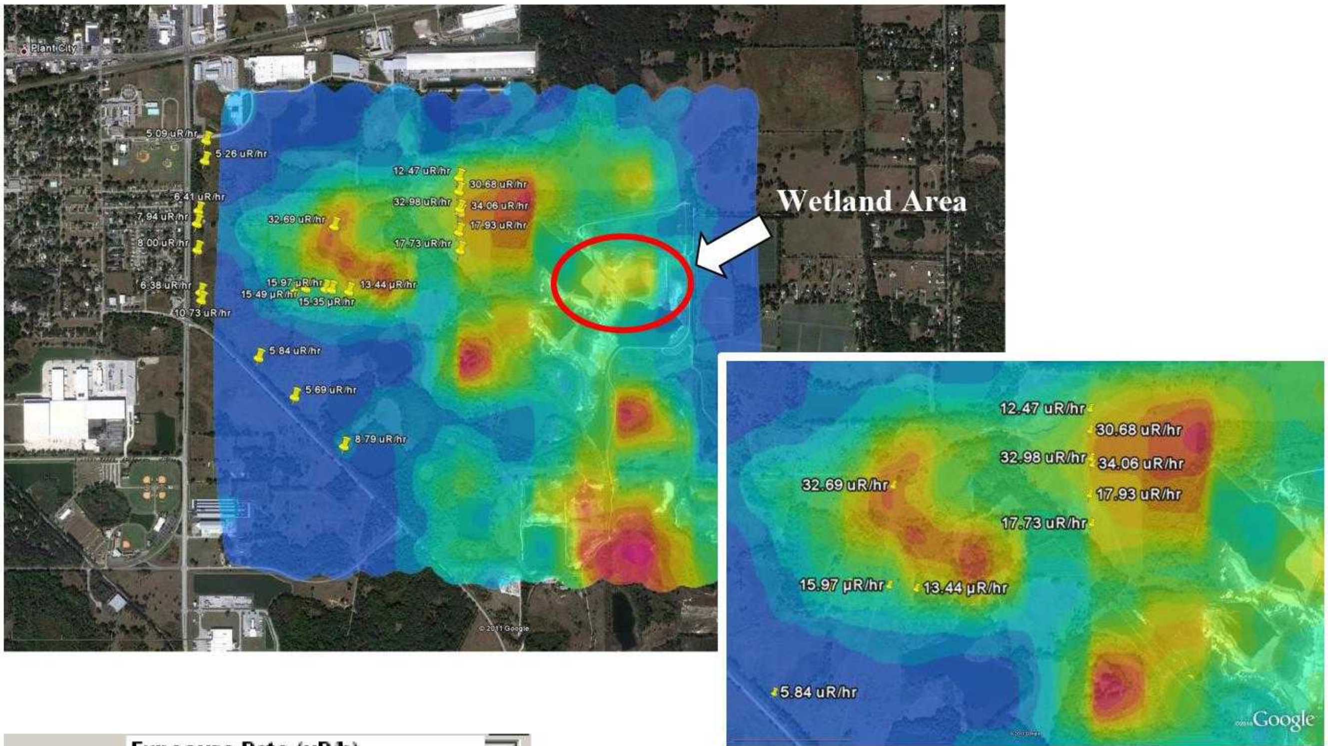
Figure 8: Sample of Ground-based Survey Data
Coronet Site, Operational Unit 2
January 10-20, 2011

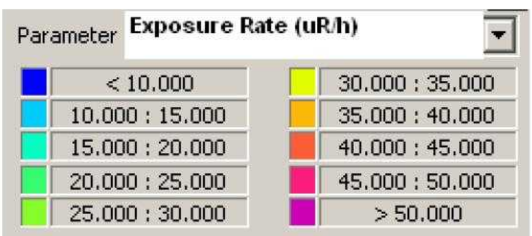


The upper left figure shows a sample of the ground-base survey results. The lower right image shows the results from the airborne survey superimposed over the ground-based results. These images illustrate the strong correlation between ground-based and airborne survey results.

This image should not be used independently to assess potential health risks. Additional information is necessary to make appropriate health-related decisions.

Figure 9: ASPECT Exposure Rate Contour (RadAssist)
Coronet Site, Operational Unit 2
January 19, 2011



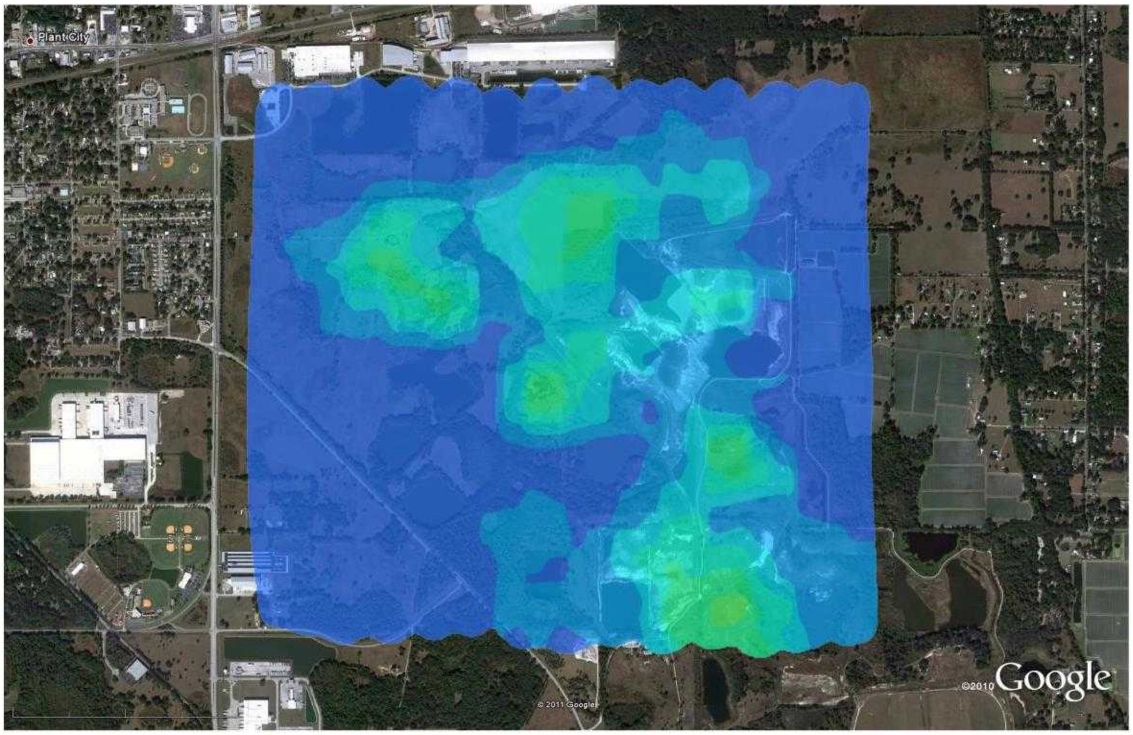


Flight Parameters
300 ft altitude
27 flight lines
300 ft line spacing
110 knots
1 second acquisition time

These images present the airborne survey results representing the exposure rate levels at 1 meter above the ground. Pressurized ionization chamber measurements were used to develop a site specific exposure-rate calibration coefficient for converting airborne count rate data to exposure rate. The lower right image shows a strong correlation between ground-based and airborne measurements. In the upper left image, note the slightly elevated exposure rate contour over a wetland area. This area was not accessible on the ground but the airborne data clearly indicate that the soils in the wetland contained elevated concentration of source materials.

This image should not be used independently to assess potential health risks.
Additional information is necessary to make appropriate health-related decisions.

Figure 10: Equivalent Uranium Concentration Contour (RadAssist)
Coronet Site, Operational Unit 2
January 19, 2011



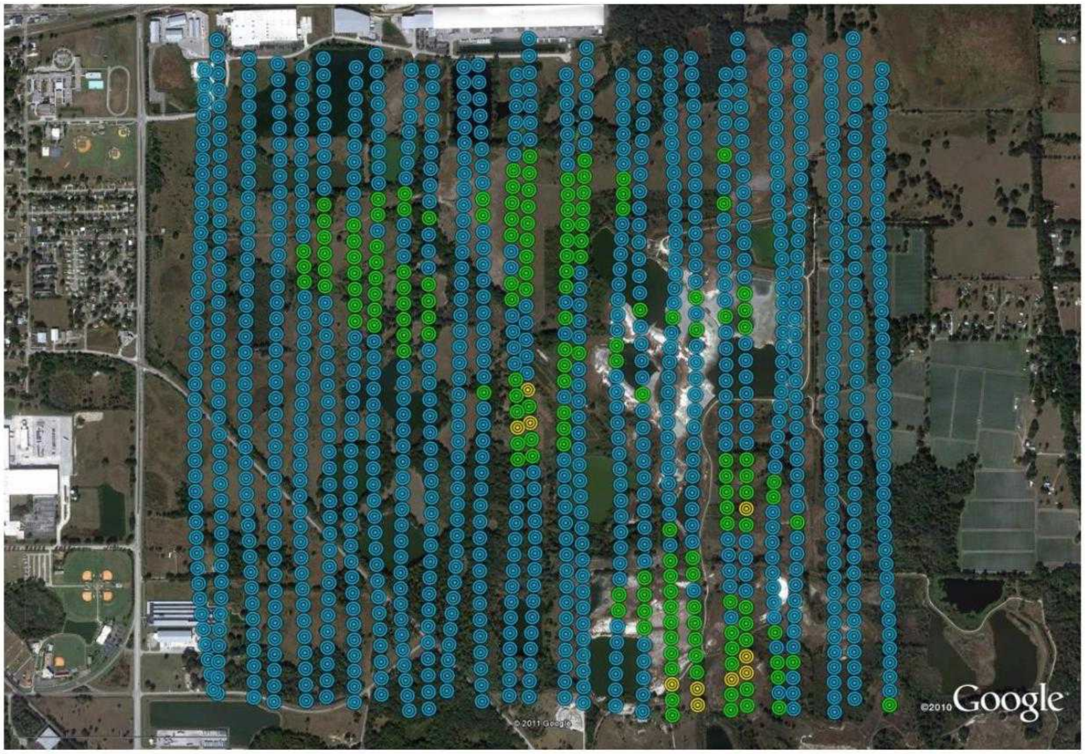
Parameter	eU Concentration (pCi/g)
< 5.0000	25.000 : 30.000
5.0000 : 10.000	30.000 : 35.000
10.000 : 15.000	35.000 : 40.000
15.000 : 20.000	40.000 : 45.000
20.000 : 25.000	> 45.000

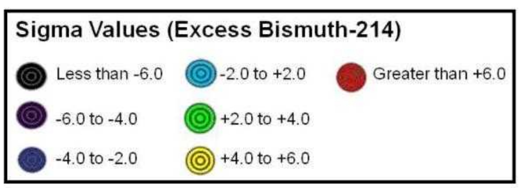
Flight Parameters
300 ft altitude
27 flight lines
300 ft line spacing
110 knots
1 /second acquisition

Equivalent uranium concentrations (pCi/g) are derived from direct measurements of the Bismuth-214, a decay product within the uranium decay chain (Appendix II). Secular equilibrium conditions are assumed to relate Bismuth-214 measurement to uranium or radium concentrations. While subsurface concentrations of gamma-emitting isotopes can be detected by the instrumentation, self- shielding of the ground limits its effective detection to a depth of about 30 centimeters. These estimates are subject to various uncertainties which are discussed in Appendix I.

This image should not be used independently to assess potential health risks. Additional information is necessary to make appropriate health-related decisions.

Figure 11: Equivalent Uranium Sigma Plot
Coronet Site, Operational Unit 2
January 19, 2011





Flight Parameters
300 ft altitude
27 flight lines
500 ft line spacing
110 knots
1 second acquisition time

This figure suggests that there are several locations (consistent with the ground-based measurements) containing excess concentrations of uranium and its decay products over a wide-area. It also suggests that the levels of contamination are slightly above the natural background (an offsite location near the Lakeland Airport), since none of these data points exceeded 6 sigma.

All the Google Earth products are available by contacting Mr. Brad Jackson, Remedial Project Manager, Region 4.

This image should not be used independently to assess potential health risks. Additional information is necessary to make appropriate health-related decisions.

Since uranium is a naturally occurring radionuclide and is ubiquitous in nature, a statistical analysis helps determine whether the uranium or its decay products are greater than the naturally occurring uranium/radium concentrations. This is referred to as a sigma plot and is discussed in Section 4. Areas on a sigma plot with values greater than 4 are very likely to contain uranium or its decay products in concentrations greater than background, while values greater than 6 sigma almost certainly indicate above background levels for uranium and its decay products. Of the 1,300 data points collected in this survey, 10 were greater than 4 sigma (standard deviations) from the mean value, and zero were greater than 6 sigma from the mean.

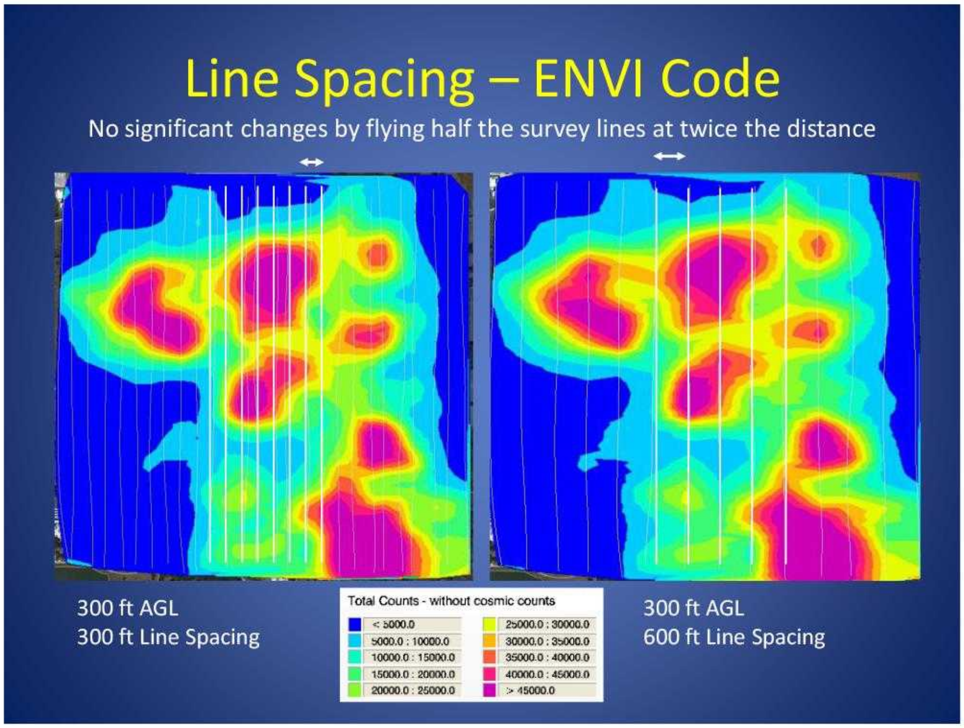
This site was surveyed at two altitudes (300 ft and 500 ft above the ground) to collect data for the purposes of demonstrating and determining the most efficient flight parameters during a response (Figures 12 & 13). Flight parameters vary according to the mission (environmental characterization, emergency response, or homeland security). This was an environmental characterization mission where the line spacing typically varies from twice the height to equal to the height of the survey. Data were collected at 300 ft lines spacing and analyzed several times by removing survey data from the total survey set and producing contour images to see the level of degradation of the resolution and correlation with ground data. Table 2 lists the analyses conducted.

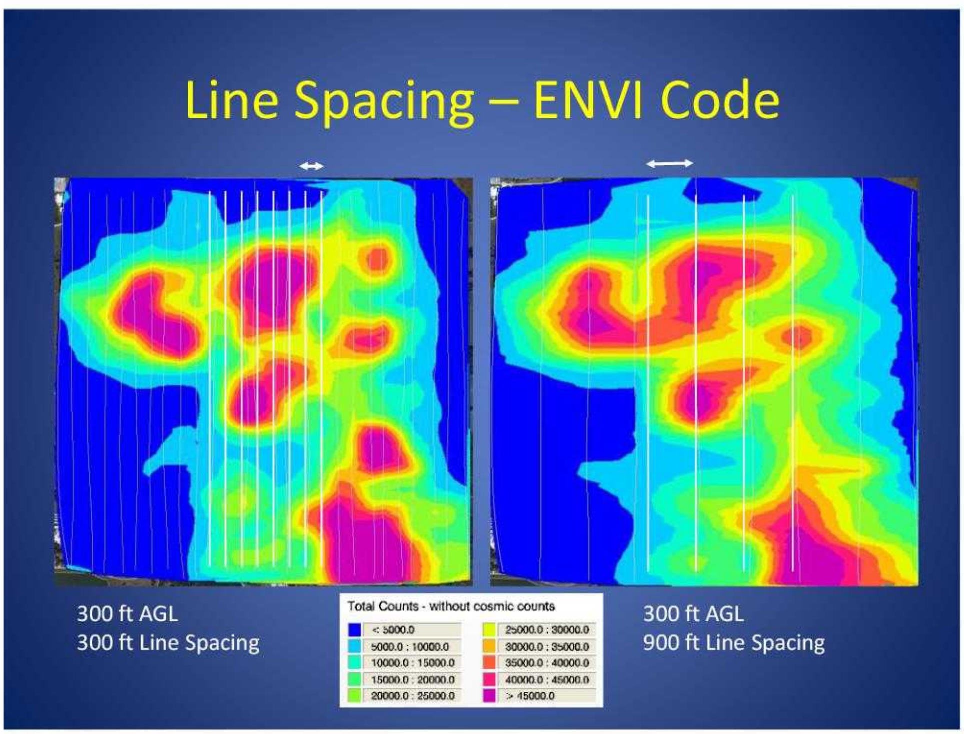
Table 2. Flight Parameters Relationship to Reference Data

Altitude (feet)	Line Spacing (feet)	Flight Lines	Comments
300	300	27	Reference Data
	600	14	Minor differences
	900	9	Moderate differences
	1,200	7	Moderate differences
	1,500	6	Moderate differences
	1,800	5	Major differences
	2,100	5*	Major differences
	2,400	4	Unacceptable
500	300	11	Compared to 300 ft reference data
	600	6	Minor differences
	900	3*	Minor differences
	1,200	3*	Moderate differences
	1,500	3*	Moderate differences

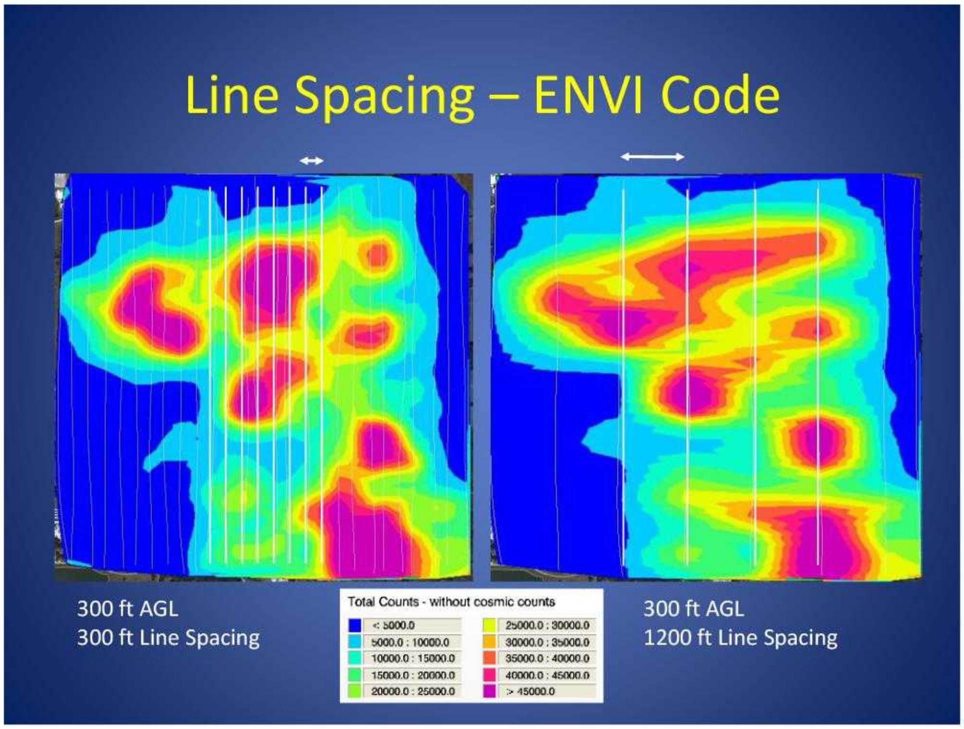
* An additional flight line was added at the eastern side of the areas to produce the contour image. To achieve the distances, different flight lines were selected to accommodate the analysis at the specified line spacing.

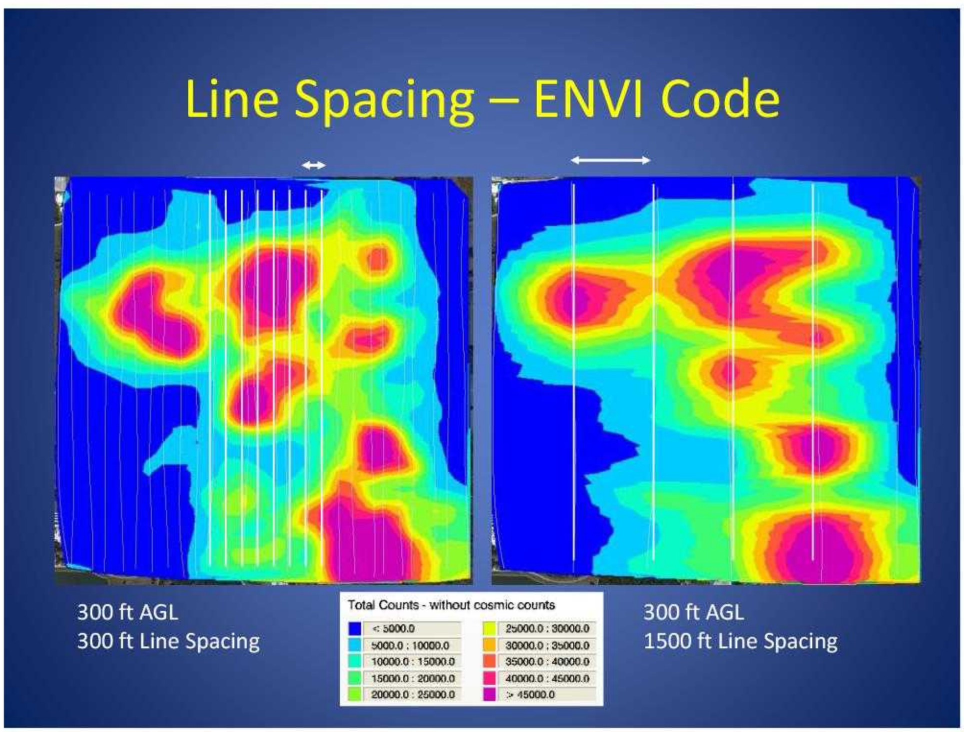
Figure 12: Comparing Flight Parameters
300 ft AGL with variable line spacings
Coronet Site, Operational Unit 2
January 19, 2011



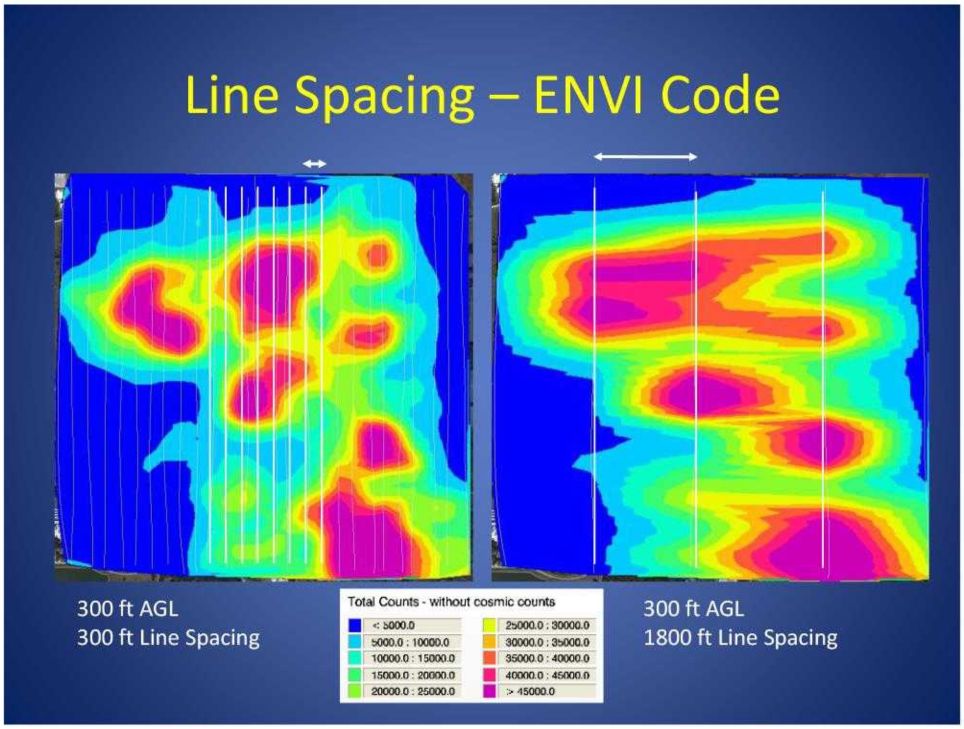


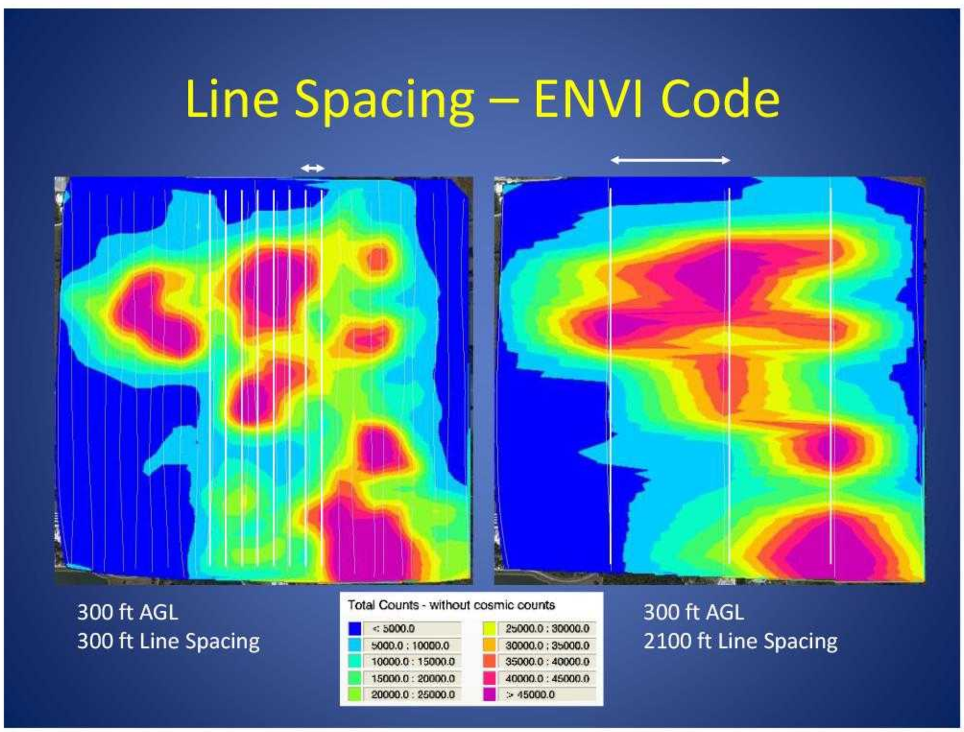
Resolution and correlation with reference data begin to degrade.



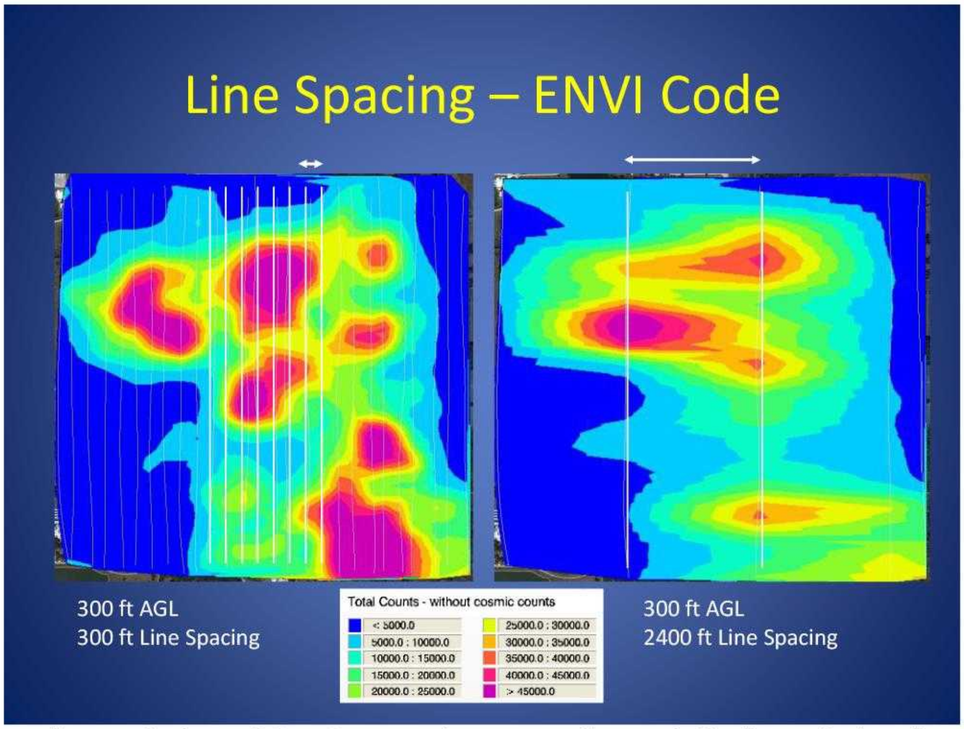


Resolution and correlation with reference data begin to degrade and source locations become more dependent on flight line location.



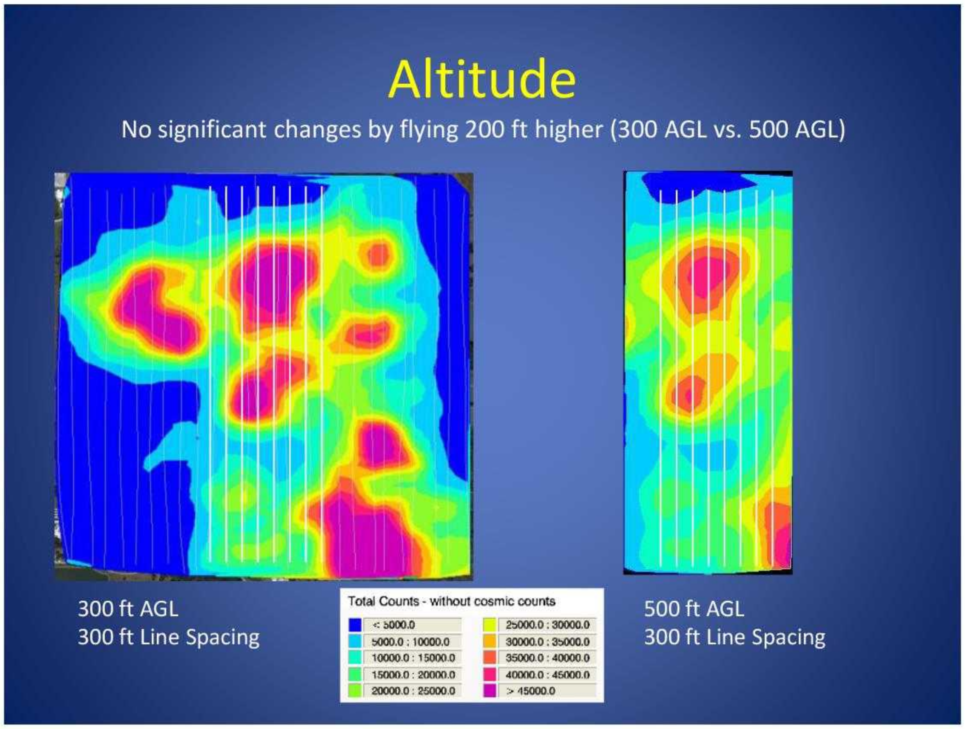


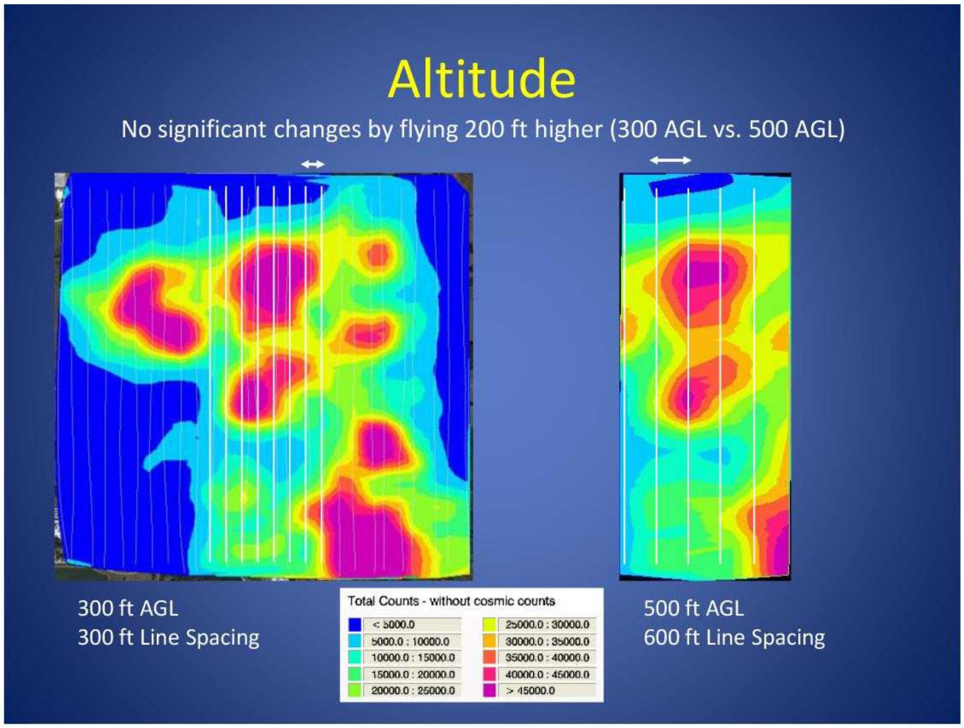
Resolution and correlation with reference data are substantially degraded and source locations are dependent on flight line location.

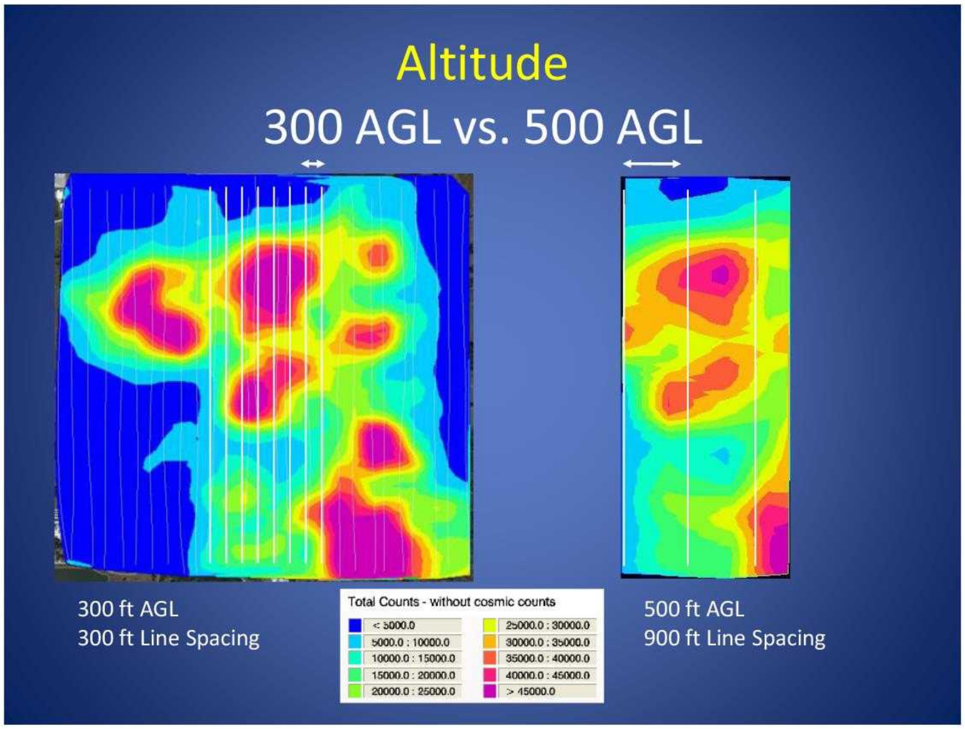


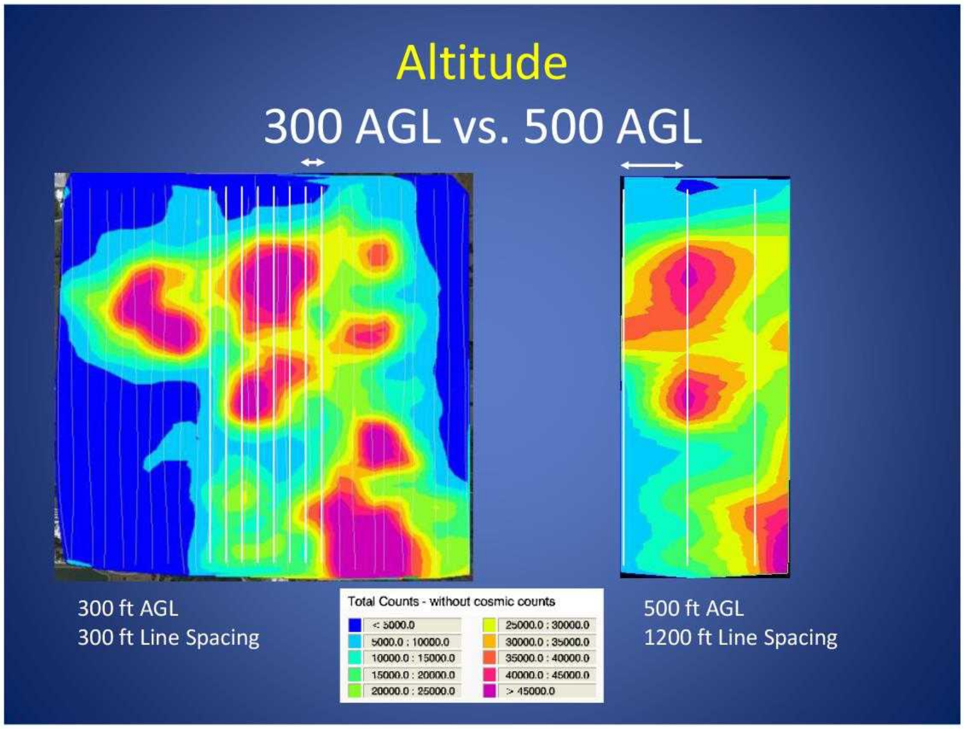
Resolution and correlation with reference data are substantially degraded and source locations are dependent on flight line location.

Figure 13:Comparing Flight Parameters
300 ft vs. 500 ft AGL with variable line spacing
Coronet Site, Operational Unit 2
January 19, 2011

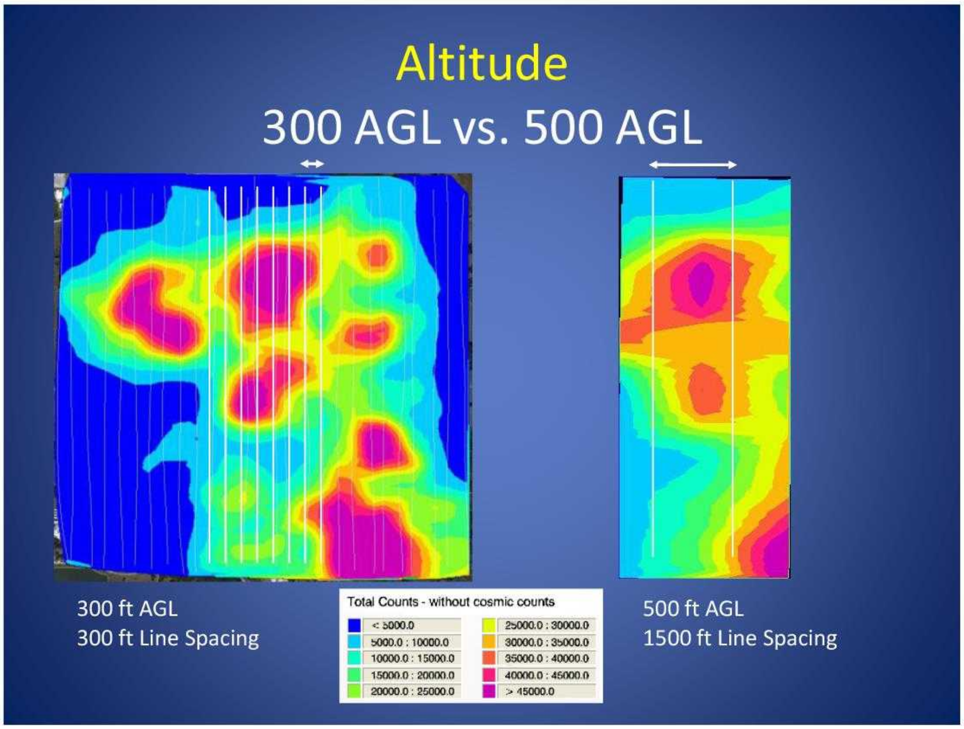








Resolution and correlation with reference data begin to degrade



Resolution and correlation with reference data begin to degrade and source locations are dependent on flight line location.

6.0 Discussion

The ability to collect scientifically valid, incident relevant, and timely data is a mandatory requirement to effectively support first response efforts associated with a radiological or nuclear release. As part of the FEMA funded (NIRT) project, the EPA ASPECT Program was tasked with formulating a level of compatibility associated with radiological airborne monitoring standard operating procedures (SOPs) with the DOE Airborne Monitoring System (AMS) program. While a majority of this effort has been associated with directly working with the AMS team on common airborne projects, the ASPECT Team had the opportunity to use an existing EPA Superfund Site as a real-world analog to study how airborne data can be used to support wide area characterization from nuclear accident or device.

Three fundamental concepts were tested in conducting this study and included:

1. an independent comparison of airborne derived estimates of gamma exposure and isotope concentration to those measured using established ground measurement techniques,
2. an analysis on the time requirements necessary to derive an airborne estimate as compared to a similar ground-based assessment, and
3. the comparison in total costs associated with conducting and developing products relevant to a first response application as compared to similar products from a ground-based survey.

As described in the body of the report, the Coronet Superfund Site (OU2) provided a real-world analog to how radiological or nuclear contamination might be distributed over a wide area. While the radiological isotopes of interest of the Site are technically enhanced natural radio-isotopes, the overall environment of the Site exhibits characteristics that will be observed in an accidental or intentional radiological nuclear release, namely that contamination is distributed over a wide area and that parts of the area are inaccessible via ground access due to terrain or water.

Due to the timing of site activities, an opportunity developed which permitted the ASPECT System to make airborne measurements concurrent to three independent ground monitoring efforts over various portions of the Site (PIC Measurements, EPA survey, and DOE survey). This action permitted an excellent multi-dimensional comparison of both airborne and ground-based data products. While the ground-based measurement techniques were limited in the number of data products generated and the aerial coverage of their respective survey areas, all systems did develop exposure estimates over regions which were likewise flown by the ASPECT System. Figure 8 illustrates an area in which ground-based exposure estimates can be directly compared to similar estimates developed with the ASPECT System. Agreement in both magnitude and aerial distribution is excellent. Other regions of elevated exposure were also found to be in excellent agreement between the airborne and ground-based methods supporting the notion that the ASPECT airborne method is scientifically valid and comparable to a similar ground-based survey. A secondary result realized during this survey was the ground surveys were unable to assess the entire terrain due to topography, vegetation and water obstacles; a limitation not present in the ASPECT survey. These findings support the conclusion that calibrated airborne systems like ASPECT have the capability to collect scientifically valid data over an affected area in an efficient fashion.

The ability to collect data in a timely fashion and develop a suitable product that is useful to the first responder is a critical component of any response system. The ASPECT Survey of OU2 required about two hours to complete. During these two hours, two airborne surveys were conducted including a 300 foot and 500 foot AGL survey. Once the data were collected, a series of semi-automated algorithms were executed that generated data products including exposure plots, excess uranium concentration plots, and statistically driven sigma plots. Total time necessary to generate, review of quality assurance, and deliver these data products required about two hours. This process has been reduced to just few minutes for emergency responses. In summary, the total time from the initiation of the survey to the potential delivery of useful data products required about four hours to complete. This excludes 10 flight hours to transport the aircraft to from its home base near Dallas, TX and a three day notice to handle logistics associated with the mission. A similar comparison to the ground survey is informative. The ground survey required about two weeks to collect a partial set of data over the area of the site with months of preparation. In addition, subsequent treatment of the collected data required an additional two to three weeks to generate exposure plots of the site. A direct comparison of the time necessary to generate a similar product to the first responder shows that the ASPECT product will be delivered in a matter of hours verses a number of days or weeks for similar ground-based data. Although, this was not an emergency response where time was of the essence, it does demonstrate the economic advantages, timeliness, accuracy, utility, and validity of airborne data for environmental characterization purposes.

While valid data and timeliness are the driving features of an effective response system, the overall operational cost of the system has to be taken into consideration. The ASPECT aircraft is normally stationed near Dallas, Texas. For the purposes of this survey, the aircraft was flown from Texas to the general survey area and returned to Texas upon the completion of the survey. The total cost of the survey, including the transition of the aircraft to and from the Site, was about $20,000. This included the operational cost of the aircraft, a crew of three, and one day of lodging and per diem. A comparison of efforts associated with the ground survey included costs associated with a crew of approximately 15 personnel working over a period of two weeks to collect a sufficient amount data to produce a data product similar to the ASPECT product. While the cost of the ground survey is not readily known, the relative comparison of the survey costs shows that the ground-based survey was at least order of magnitude greater than the ASPECT airborne survey.

The purpose of this brief discussion is not to discredit the use of a ground-based survey or to suggest that all radiological or nuclear response measurements can be conducted from an airborne platform, but to identify how airborne measurement techniques can provide scientifically valid and comparable results to those collected using ground-based methods. Likewise, in situations that require timely data over wide areas of contamination, the airborne methods pose advantages in both timeliness of data product delivery and overall survey costs. This survey also provided critical data to illustrate the affects of various flight parameters and permitted the ASPECT program to optimize environmental characterization missions for costs while delivering a scientifically valid product.

Acknowledgements

The ASPECT team would like to acknowledge Brad Jackson, Region 4 Remedial Project Manager, for his support and coordination of this aerial survey.

Appendix I

Discussion - Radiological Uncertainties Associated with \Airborne Systems

Ideally, the airborne radiation measurements would be proportional to the average surface concentrations of radioactive materials (mainly NORM). However, there are several factors that can interfere with this relationship causing the results to be over- or under-estimated, as described below. Additionally, two other sections discuss how data are interpreted and airborne measurement data are compared to surface measurements.

Background radiation

Airborne gamma-spectroscopy systems measure radiation originating from terrestrial, radon, aircraft, and cosmic sources. To obtain only the terrestrial contribution, all other sources need to be accounted for (subtracted from the total counts), especially for this survey where small differences are important. Radon gas is mobile and can escape from rocks and soil and accumulate in the lower atmosphere. Radon concentrations vary from day to day, with time of day, with weather conditions (e.g., inversions and stability class), and with altitude. It is the largest contributor among background radiation and its daughter product, ^{214}Bi, is used to estimate radium and uranium concentration in the soil. Radon is accounted for in the processing algorithm by flying specific test lines before and after each survey and comparing the results. Cosmic and aircraft radiation (e.g., instrument panels and metals containing small amounts of NORM) also provide a small contribution to the total counts. These are accounted for in the processing algorithm by flying a "high-altitude" or "water-" test line and subtracting these contributions for the survey data.

Secular Equilibrium Assumption

Secular equilibrium is assumed in order to estimate uranium concentrations from one of its daughter products, ^{214}Bi. Secular equilibrium exists when the activity of a daughter product equals that of its parent radionuclide. This can only occur if the half-life of the daughter product is much shorter than its parent and the daughter product stays with its parent in the environment. In this case, the measurement of ^{214}Bi gamma emission is used to estimate the concentration of its parent radionuclide if one assumes all the intermediate radionuclides stay with each other. However, ^{222}Rn is a noble gas with a half-life of 3.8 day and may degas from soils and rocks fissures due to changes in weather conditions. Due to the relatively long half-life and the combined effect of radon gas mobility and environmental "chemical" migration, it is not certain whether the secular equilibrium assumption is reasonable at any given site. In addition, human intervention in this natural chain of events may have caused an increased uncertainty in uranium concentration estimates.

Atmospheric Temperature and Pressure

The density of air is a function of atmospheric temperature and pressure. Density increases with cooler temperatures and higher pressures, causing a reduction in detection of gamma-rays. This reduction in gamma-ray detection is called attenuation and it is also a function of the gamma-ray energy. Higher energy gamma-rays are more likely to reach the detectors than lower energy gamma-rays. For example, 50% of the ^{214}Bi 1.76 MeV gamma-rays will reach the detector at an altitude of 300 ft whereas only 44% of the ^{40}K 1.46 MeV gamma-rays will reach the detector.[*] Temperature and pressure changes contribute little to the overall uncertainties associated with airborne detection systems as compared to other factors.

Soil moisture and Precipitation

Soil moisture can be a significant source of error in gamma ray surveying. A 10% increase in soil moisture will decrease the total count rate by about the same amount due to absorption of the gamma rays by the water. Snow cover will cause an overall reduction in the total count rate because it also attenuates (shields) the gamma rays from reaching the detector. About 4 inches of fresh snow is equivalent to about 33 feet of air. There was no significant precipitation during this survey. While subsurface concentrations of gamma-emitting isotopes can be detected by the instrumentation, self- shielding of the ground limits its effective detection to a depth of about 30 centimeters.[2]

Topography and vegetation cover

Topographic effect can be severe for both airborne and ground surveying. Both airborne and ground-based detection systems are calibrated for an infinite plane source which is referred to as 2π geometry (or flat a surface). If the surface has mesas, cliffs, valleys, and large height fluctuations, then the calibration assumptions are not met and care must be exercised in the interpretation of the data. Vegetation can affect the radiation detected from an airborne platform in two ways: (1) the biomass can absorb and scatter the radiation in the same way as snow leading to a reduced signal, or (2) it can increase the signal if the biomass concentrated radionuclides found in the soil nutrients.

Spatial Considerations

Standard ground-based environmental measurements are taken 3 ft above the ground with a field of view of about 30 ft^2. The ASPECT collected data at about 300 ft above the ground with an effective field of view of about 6.5 acres. These aerial measurements provide **an average surface activity over the effective field of view**. If the ground activity varies significantly over the field of view, then the results from ground- and aerial-based systems may not agree. It is not unusual to have differences as much as several orders of magnitude depending on the survey altitude and the size and intensity of the source material. For example, in the figures below, if the "A" circle represents the detector field of view and the surrounding area had no significant differences in surface activity, a 300 ft aerial measured could correlate to a ground-based exposure rate of 3.5 µR/h. However, if all the activity was contained in a small area such as a single small structure containing uranium tailings (represented by the blue dot within the field of view of "B"), a 300 ft aerial measurement may still provide the same exposure rate measurement but the actual ground-based measurements could be as high as 3,150 µR/h.

[*] Attenuation coefficients of $0.0077 m^{-1}$ for 1.76 MeV and $0.0064 m^{-1}$ for 1.46 MeV.

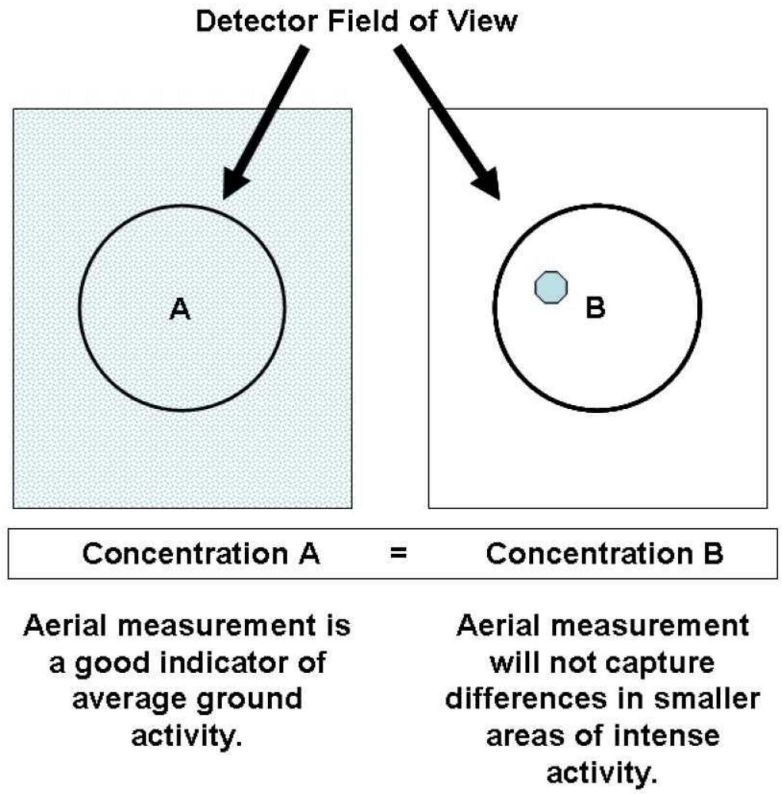


Illustration of aerial measurement capabilities and interpretation of the results

Comparing ground samples and airborne measurements

Aerial measurements are correlated to ground concentrations through a set of calibration coefficients. The ASPECT calibration coefficients for exposure-rate, potassium, uranium, and thorium concentrations were derived from a well characterized "calibration" strip of land near Las Vegas, Nevada. *In-situ* gamma spectroscopy and pressurized ionization chambers measurements were used to characterize the area. One must exercise caution when using a laboratory to analyze soil samples to verify or validate aerial measurements because differences will occur. In addition to local variations in radionuclide concentrations, which are likely to be the most significant issue, differences may arise due to laboratory processing. Laboratory processing typically includes drying, sieving and milling. These processes remove soil moisture, rocks and vegetation, and will disrupt the equilibrium state of the decay chains due to liberation of the noble gas radon. Thus reliance on ^{208}Tl and ^{214}Bi as indicators of ^{232}Th and ^{238}U (as is assumed for aerial surveying) is made more complex. In addition, aerial surveys cannot remove the effects of vegetation on gamma flux. Intercomparisons must minimize these differences and recognize the effects of differences that cannot be eliminated.

Geo-Spatial Accuracy

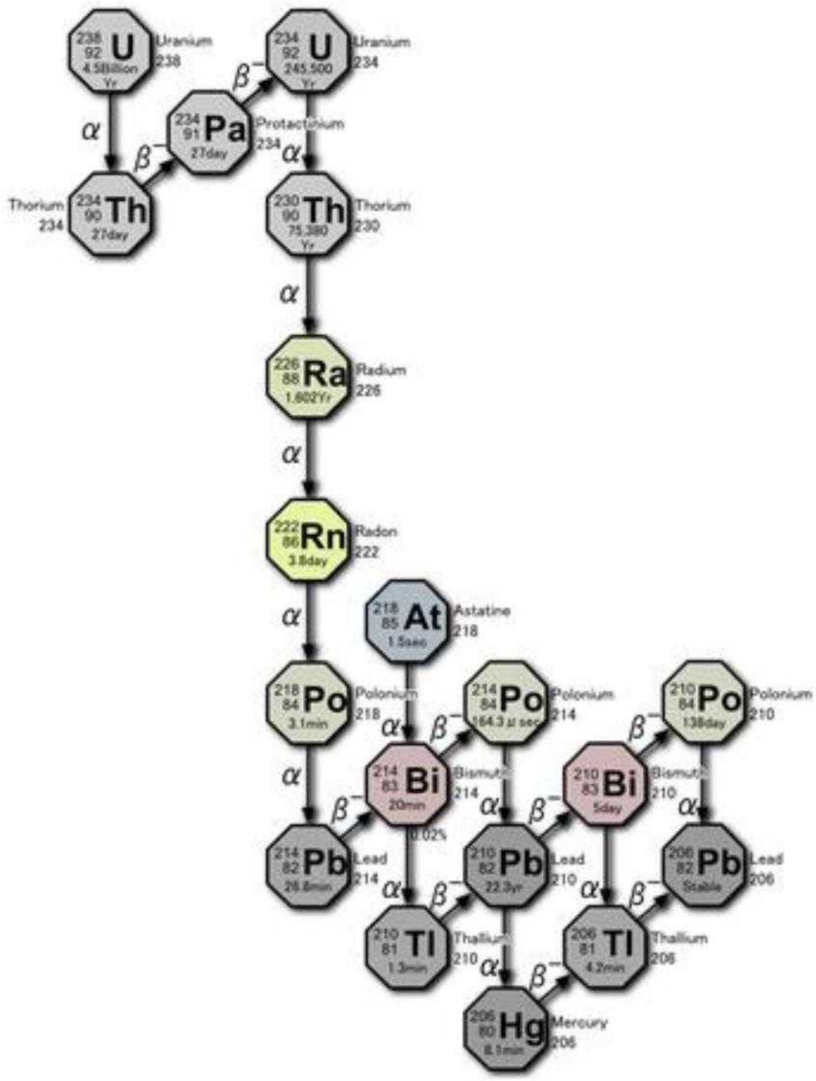
All aerial measurements collected by the ASPECT aircraft are geo-coded using latitude and longitude. The position of the aircraft at any point in time is established by interpolating between positional data points of a non-differential global positioning system and referencing the relevant position to the time that the measurement was made. Time of observation is derived from the aircraft computer network which is synchronized from a master GPS receiver and has a maximum error of 1 second*. Timing events based on the network running the Windows-based operating system and the sensor timing triggers have a time resolution of 50 milliseconds, so the controlling error in timing is the network time. If this maximum timing error is coupled to the typical ground velocity of 55 meter sec of the aircraft, an instantaneous error of 55 meters is possible due to timing. In addition, geo-positional accuracy is dependent on the instantaneous precision of the non-differential GPS system which is typically better than 30 meters for any given observation. This results in an absolute maximum instantaneous error of about 80 meters in the direction of travel.

For measurements dependent on aircraft attitude (photographs, IR images) three additional errors are relevant and include the error of the inertial navigation unit (INU), the systemic errors associated with sensor to INU mounting, and altitude errors above ground. Angular errors associated with the INU are less than 0.5 degrees of arc. Mounting error is minimized using detailed bore alignment of all sensors on the aircraft base plate and is less than 0.5 degrees of arc. If the maximum error is assumed then an error of 1.0 degree of arc will result. At an altitude of 150 meters (about 500 feet) this error translates to about 10 meters. Altitude above ground is derived from the difference in the height above the geoid (taken from the GPS) from the ground elevation derived from a 30 meter digital elevation model. If an error of the model is assumed to be 10 meters and the GPS shows a typical maximum error of 10 meters, this results in an altitude maximum error of 20 meters in altitude error. If this error is combined with attitude and the instantaneous GPS positional error (assuming no internal receiver compensation due to forward motion) then an error of about 50 meters will result. The maximum forecasted error that should result from the aircraft flying straight and level is + - 130 meters in the direction of travel and + - 50 meters perpendicular to the direction of travel. Statistical evaluation of collected ASPECT data has shown that typical errors of + - 22 meters in both the direction of and perpendicular to travel are typical. Maximum errors of + - 98 meters have been observed during high turbulence conditions.

* The ASPECT network is synchronized to the master GPS time at system start-up. If the observed network GPS time difference exceeds 1 sec. at any time after synchronization, the network clock is reset.

Appendix II

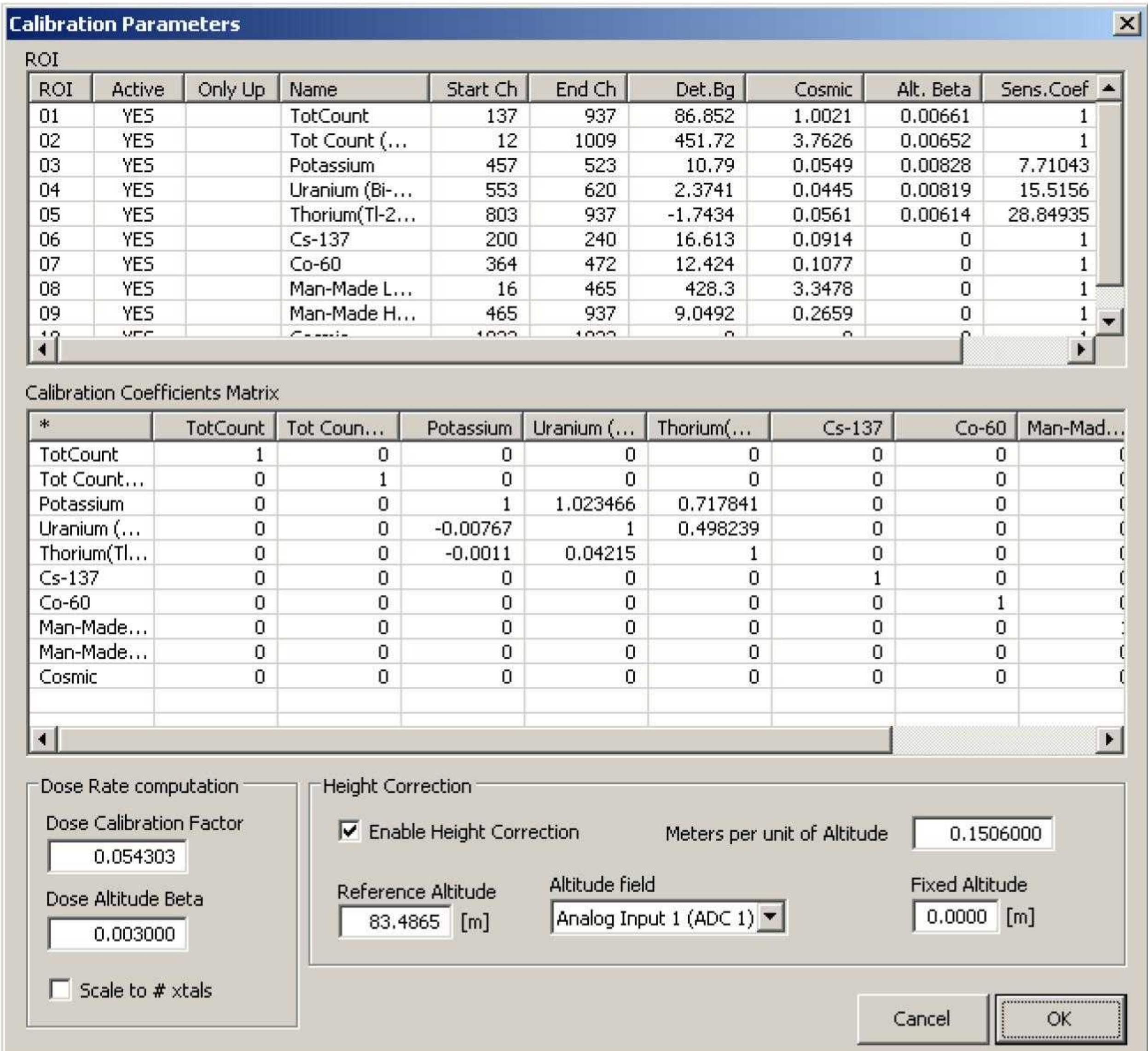
Uranium 238 decay series



Appendix III

RadAssist Calibration Parameters

RadAssist calibration parameters for Coronet Survey on January 19, 2011.



Calibration Parameters

ROI

ROI	Active	Only Up	Name	Start Ch	End Ch	Det.Bg	Cosmic	Alt. Beta	Sens.Coef
01	YES		TotCount	137	937	86.852	1.0021	0.00661	1
02	YES		Tot Count (...	12	1009	451.72	3.7626	0.00652	1
03	YES		Potassium	457	523	10.79	0.0549	0.00828	7.71043
04	YES		Uranium (Bi-...	553	620	2.3741	0.0445	0.00819	15.5156
05	YES		Thorium(Tl-2...	803	937	-1.7434	0.0561	0.00614	28.84935
06	YES		Cs-137	200	240	16.613	0.0914	0	1
07	YES		Co-60	364	472	12.424	0.1077	0	1
08	YES		Man-Made L...	16	465	428.3	3.3478	0	1
09	YES		Man-Made H...	465	937	9.0492	0.2659	0	1

Calibration Coefficients Matrix

*	TotCount	Tot Coun...	Potassium	Uranium (...	Thorium(...	Cs-137	Co-60	Man-Mad...
TotCount	1	0	0	0	0	0	0	
Tot Count...	0	1	0	0	0	0	0	
Potassium	0	0	1	1.023466	0.717841	0	0	
Uranium (...	0	0	-0.00767	1	0.498239	0	0	
Thorium(Tl...	0	0	-0.0011	0.04215	1	0	0	
Cs-137	0	0	0	0	0	1	0	
Co-60	0	0	0	0	0	0	1	
Man-Made...	0	0	0	0	0	0	0	
Man-Made...	0	0	0	0	0	0	0	
Cosmic	0	0	0	0	0	0	0	

Dose Rate computation

Dose Calibration Factor: 0.054303

Dose Altitude Beta: 0.003000

☐ Scale to # xtals

Height Correction

☑ Enable Height Correction

Meters per unit of Altitude: 0.1506000

Reference Altitude: 83.4865 [m]

Altitude field: Analog Input 1 (ADC 1)

Fixed Altitude: 0.0000 [m]

Cancel OK

This screen-shot from the RadAssist Program shows the calibration coefficients used in the determination of eUranium concentrations for this report.

Appendix IV
Environmental Background Radiation

Naturally occurring radioactive material (NORM) originates from cosmic radiation, cosmogenic radioactivity, and primordial radioactive elements that were created at the beginning of the earth. Cosmic radiation consists of very high energy particles from extraterrestrial sources such as the sun (mainly alpha particles and protons) and galactic radiation (mainly electrons and protons). Its intensity increases with altitude, doubling about every 6,000 ft, and with increasing latitude north and south of the equator. The cosmic radiation level at sea level is about 3.2 µR/h and nearly twice this level in locations such as Denver, CO.

Cosmogenic radioactivity results from cosmic radiation interacting with the earth's upper atmosphere. Since this is an ongoing process, a steady state has been established whereby cosmogenic radionuclides (e.g., ^{3}H and ^{14}C) are decaying at the same rate as they are produced. These sources of radioactivity were not a focus of this survey and were not included in the processing algorithms.

Primordial radioactive elements found in significant concentrations in the crustal material of the earth are potassium, uranium and thorium. Potassium is one of the most abundant elements in the Earth's crust (2.4% by mass). One out of every 10,000 potassium atoms is radioactive potassium-40 (^{40}K) with a half-life (the time it takes to decay to one half the original amount) of 1.3 billion years. For every 100 ^{40}K atoms that decay, 11 become Argon-40 (^{40}A) and emit a 1.46 MeV gamma-ray.

Uranium is ubiquitous in the natural environment and is found in soil at various concentrations with an average of about 1.2 pCi/g. Natural uranium consists of three isotopes with about 99.3% being uranium-238 (^{238}U), about 0.7% being uranium-235 (^{235}U), and a trace amount being uranium-234 (^{234}U). The tenth daughter product of ^{238}U, bismuth-214 (^{214}Bi), is used to estimate the presence of radium and uranium by its 1.76 MeV gamma-ray emission.

Thorium-232 is the parent radionuclide of one of the 4 primordial decay chains. It is about four times more abundant in nature than uranium and also decays through a series of daughter products to a stable form of lead. The thorium content of rocks ranges between 0.9 pCi/g and 3.6 pCi/g with an average concentration of about 1.3 pCi/g.[3] The ninth daughter product, thallium-208 (^{208}Tl), is used to estimate the presence of thorium by its 2.61 MeV gamma-ray emission.

Technologically enhanced naturally occurring radioactive material (TENORM) is NORM processed in such a manner that its concentration has been increased. TENORM is associated with various industries including energy production, water filtration, fertilizer production, mining and metals production. Concentrations of radionuclides in TENORM are often orders of magnitude greater than the naturally occurring concentrations. This survey was designed to identify areas where the TENORM concentrations were significantly higher than the natural background concentrations due to the mining and processing of uranium ore.

Appendix V

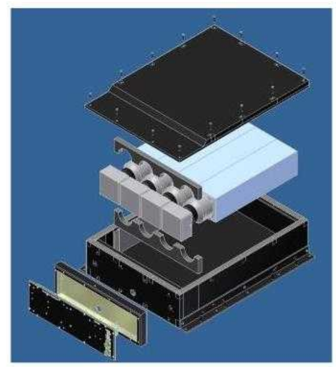
ASPECT Instrumentation

Survey Instrumentation

The ASPECT aircraft is a twin engine, high wing AeroCommander 680FL capable of cruising speeds ranging from about 100 knots (115 mph) to 200 knots (230 mph) (Image 2). It is based in Waxahachie, Texas and operated by two pilots and one technician. A suite of chemical, radiological, and photographic detection technology is mounted within the airframe making it the only aircraft in the nation with remote chemical and radiological detection capabilities.

Radiation Detectors

The radiological detection technology consisted of two RSX-4 Units (Radiation Solutions, Inc., 386 Watline Avenue, Mississauga, Ontario, Canada) (Image 9). Each unit was equipped with four 2"x4"x16" thallium-activated sodium iodide (NaI[Tl]) scintillation crystals for a total of 8 NaI[Tl] (16.8 L) crystals. The aircraft is capable of be equipped with up to 16 crystals if warranted by the mission requirements. In addition, ASPECT is capable of equipping three 3"x3" $LaBr_3$:Ce scintillating crystals.



RSX-4 unit showing four detector locations.

Detector packs for airborne spectroscopy typically consist of clusters of NaI[Tl] crystals because they are relatively inexpensive compared to other scintillation crystals. In addition, NaI crystals have high sensitivity with acceptable spectral resolution (approximately seven percent full width at half maximum (FWHM)[*] at 662 keV), and are easy to maintain.

The Radiation Solutions RSX-4 unit was specifically designed for airborne detection and measurement of low-level gamma radiation from both naturally occurring and man-made sources. It uses advanced digital signal processing and software techniques to produce spectral data equivalent to laboratory quality. The unit is a fully integrated system that includes an individual high resolution (1,024 channel) advanced digital spectrometer for each detector. A high level of self diagnostics and performance verification routines such as auto gain stabilization are implemented with an automatic error notification capability, assuring that the resulting maps and products are of high quality and accuracy.

The ASPECT program calibrates it radiological instrumentation annually according to the International Atomic Energy Agency specifications.[4]

Chemical Sensors

Image 14: View of chemical sensors: high speed infrared spectrometer, lower left corner; infrared line scanner is out of view behind the line scanner.

The chemical sensors installed in the aircraft detect the difference in infrared spectral absorption or emission of a chemical vapor. The first sensor is a model RS-800, multi-spectral IR-Line Scanner (Raytheon TI Systems, McKinney, TX) (Image 4). It is a multi-spectral high spatial resolution infrared imager that provides two-dimensional images. Data analysis methods allow the operator to process the images containing various spectral wavelengths into images that indicate the presence of a particular chemical species.
The second sensor is a modified model MR254/AB (ABB, Quebec, Quebec City, Canada). It is a high throughput Fourier Transform Infrared Spectrometer (FT-IR) that collects higher spectral resolution of the infrared signature from a specific plume location. The instrument is capable of collecting spectral signatures with a resolution selectable between 0.5 to 32 wave-numbers.

The principle of measurement involves the detection, identification, and quantification of a chemical vapor species using passive infrared spectroscopy. Most vapor compounds have unique absorption spectral bands at specific frequencies in the infrared spectral region. Careful monitoring of the change in total infrared radiance levels leads to concentration estimations for a particular vapor species.

Camera

The ASPECT aircraft uses a high resolution digital camera to collect visible aerial images. The camera consists of a Nikon D2X SLR camera body with a fixed focus (infinity) 24mm F1.2 Nikor lens. The camera sensor has 12.5 million pixels (12.2 Mpixels viewable) giving a pixel count of 4288 x 2848 in a 3:2 image ratio. An effective ground coverage area of 885 x 590 meters is obtained when operated from the standard altitude of 850 meters.

Image ortho-rectification, which corrects for optical distortion and geometric distortion due to the three dimensional differences in the image, is accomplished using an inertial navigation unit (pitch, roll, and heading) coupled with a dedicated 5 Hz global positioning system (GPS). Aircraft altitude above ground is computed using the difference between the indicated GPS altitude and a 30 meter digital elevation model (DEM). Full ortho-rectification is computed using a camera model (lens and focal plane geometric model) and pixel specific elevation geometry derived from the digital elevation model to minimize edge and elevation distortion. Documented geo-location accuracy is better than 49 meters.

Radiological spectral data are collected every second along with GPS coordinates and other data reference information. These data are subject to quality checks within the Radiation Solutions internal processing algorithms (e.g. gain stabilization) to ensure a good signal. If any errors are encountered with a specific crystal during the collection process, an error message is generated and the data associated with that crystal are removed from further analyses.

Prior to the survey, the RSX-4 units go through a series of internal checks. If no problems are detected, a green indicator light notifies the user that all systems are good. A yellow light indicates a gain stabilization issue with a particular crystal. This can be fixed by waiting for another automatic gain stabilization process to occur or the user can disable the particular crystal via the RadAssist Software application. A red light indicates another problem and would delay the survey until it can be resolved.

Satellite Communications

The ASPECT aircraft uses a broadband satellite system to provide near real-time data communication. The broadband option provides reliable conductivity for the entire continental United States and consists of a Chelton FAA certified phased array antenna[*] coupled with a high-rate magnetometer to provide antenna steering. One master transceiver is coupled with a power amplifier to provide a 300kilobyte (KB) down-load speed into the aircraft and a 100KB up-load speed from the aircraft. Integrated with the transceiver is a standard ethernet router providing full port forwarding capability.

Radar Altimeter

A FreeFlight Systems TRA 3000 Radar Alimeter[†] provides height measurements above ground level (AGL) from 12 m up to 760 m. Typical radiological missions are between 91 m and 150 m with altimeter accuracy of about five percent. The digital output is fed into the Radiation Solutions RSX-4 unit which feeds into the RadAssist software that corrects the spectral data for altitude attenuation.

ASPECT internal algorithms can also determine altitude above ground by using the difference between the indicated GPS altitude and a 30 meter digital elevation model (DEM) or the height above eplisoid (HAE) provided by the GPS. So in case of an equipment failure, the system has alternative methods to process altitude data.

[*] Chelton, 1955 Lakeway Drive, Suite 200, Lewisville, TX 75057, www.cheltoninc.com

[†] Free*Flight* Systems, 3700 Interstate 35 South Waco, TX 76706. Freeflightsystems.com

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